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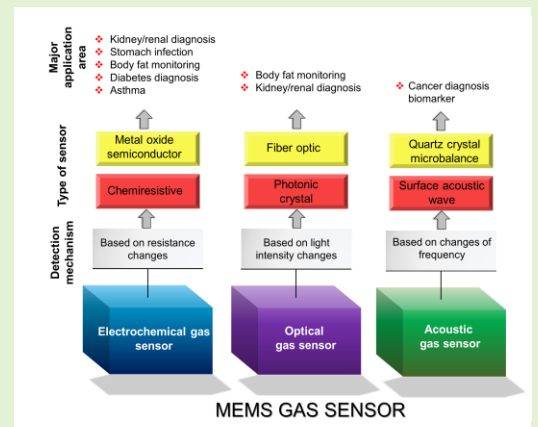
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MEMS Gas Sensors: A Review

Muhammad Izzudin Ahmad Asri, Md. Nazibul Hasan, Mariatul Rawdhah Ahmad Fuaad, Yusri Md Yunos, and Mohamed Sultan Mohamed Ali, *Senior Member, IEEE*

Abstract—Micro-electromechanical system (MEMS) gas sensors represent a system that is capable of detecting the existence and concentration of gasses in the atmosphere. These sensors have become incredibly popular and have been widely used in a variety of fields, including the biomedical field. Over the years, several gas sensors have been developed to detect and analyze a wide range of gases. As sensor applications are expected to be further extended in the near future, it is, therefore, essential to review crucial types of gas sensors, their features, challenges, and a range of important applications. This paper presents a comprehensive review of the state-of-the-art gas sensors, which have been developed for gas sensing applications using MEMS technology. The working principle, the structure, the sensitive material and the important characteristics of each of these sensors are discussed. The focus of this review is on applications surrounding the use of electrochemical, optical and acoustic gas sensors for biomedical applications.

Index Terms—MEMS, gas sensor, electrochemical, optical, acoustic gas sensor, and medical gas sensor.



I. INTRODUCTION

DUE to rapid urbanization and industrialization, the world today faces a problem of serious air pollution, as observed by the increasing amounts of harmful and polluting gases being released into the environment. These pollutants consist of several volatile organic compounds (VOCs), and toxic gases such as carbon dioxide, ammonia, benzene, ethanol and formaldehyde. The presence of toxic gases and VOCs are detrimental to humans and the surrounding atmosphere. Severe air pollution can cause a decrease in the function of the lungs and lung damage, making humans much more vulnerable to diseases such as MERS-CoV, and COVID-19 [1, 2]. Thus, air pollution has become a serious global issue, which has driven several health agencies to recommend short-term exposure limits (STELs) for various toxic and VOCs gases. Therefore, effective methods to monitor toxic gases and VOCs are in demand for atmospheric environmental

measurements and control, as well as human well-being and health monitoring. Accordingly, highly sensitive analytical techniques such as gas chromatography (GC), spectrophotometry, and high-performance liquid chromatography (HPLC), have been used for accurate quantification of these gases. Despite their accuracy and precision, these techniques generally have some drawbacks, such as cost, lack of portability, and high-power demand. Furthermore, the use of such techniques often requires complex and time-consuming pre-treatment steps, and highly skilled operators. Clearly, these procedures cannot provide gas exposure information on a real-time basis. Therefore, inexpensive, small, and user-friendly gas sensing devices are highly needed. Hence, the presence of MEMS is significant, whereby, microelectromechanical systems (MEMS) based techniques have been introduced in gas sensing applications [3]. The MEMS gas sensing mechanisms such as electrochemical, optical, and acoustics, are developed because of advantageous features such as higher sensitivity, lower power consumption, smaller designs, and a much lower fabrication cost, compared to the traditional gas sensors [4-6]. In addition, these MEMS gas sensors are not only used for monitoring pollutant gases but also used in other applications, such as to diagnose health-related issues [7, 8], food testing and analysis [9, 10], pipeline leakage detection [11], and agriculture [12]. However, each of these MEMS gas sensing methods have unique features and limitations, thus, a suitable sensing method needs to be selected for a particular application.

A number of studies and surveys have previously been reported on gas sensors. For instance, Shoubi et al. [13]

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studied the frameworks and challenges of gas sensing technologies. Other researchers focused on sensing a specific type of gas, such as ammonia [14], hydrogen [15], and toxic gases [16]. Other researchers focused on sensitive materials for gas detection, such as metal oxide [16-18], nanosheet materials [17, 19], 2D nanomaterials [20, 21], Carbon nanotubes (CNT) [22], and conducting polymers [23, 24]. Lozano et al. [25] and Rohaizad et al. [26] reviewed the application of the gas sensors in the biomedical field, while Li et al. [27] focused on automotive applications. This review reports on three major MEMS gas sensors, i.e., electrochemical, optical, and acoustic-based sensors for biomedical applications. The configuration, mechanism, fabrication, and performance of these gas sensors are thoroughly discussed. Fig. 1 shows the visual structure of the review paper for three major classes of MEMS gas sensors. This review is organized as follows; structure, working principle, and essential features of MEMS gas sensors according to their characteristics, i.e., electrochemical, optical, and acoustic gas sensors, which are discussed in section II. In addition, section III discusses gas sensors for biomedical applications. Finally, the review concludes with a synopsis of the main outcomes and offers a multitude of perspectives in section IV.

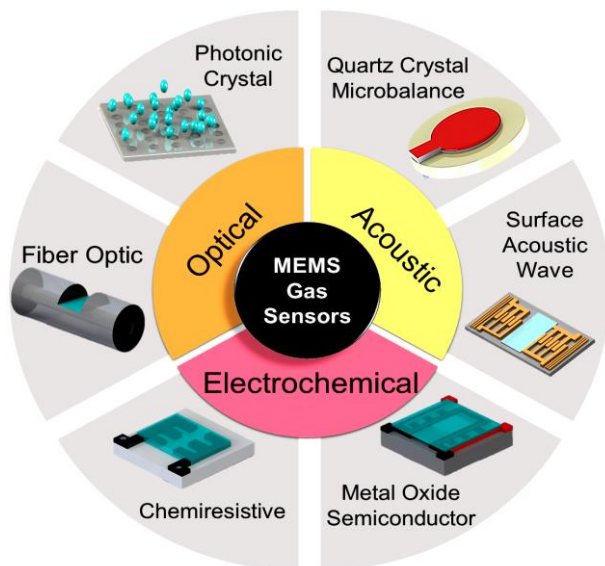


Fig. 1. Graphical overview of this review paper.

II. TYPE OF GAS SENSORS

In this section, an overview of the major MEMS gas sensors, i.e., electrochemical, optical, and acoustic gas sensors, is presented by emphasizing the performance enhancement factors for each of them. The highest performance factor obtained for each of the MEMS gas sensors have been discussed in the sub-section.

A. Electrochemical Gas Sensor

The electrochemical sensor operates by measuring the chemical reactions through absorption and de-absorption

processes on the sensing material's surface. Once the sensing material's conductivity is changed, it can be transduced as a measurable electrical signal. MOS and chemiresistive gas sensors are listed in the same category as electrochemical gas sensors.

1) *Metal Oxide Semiconductor (MOS)*: In the early sixties, the first metal oxide gas sensor was invented using zinc oxide (ZnO) films to sense carbon dioxide gas [28]. Since then, the MOS sensing technology has been widely explored to improve its capability for a much more diverse range of applications. The basic design consists of sensing layers, substrates, two contact electrodes, and a heating element between the substrate and sensing material, as shown in Fig. 2a. Generally, MOS-based gas sensors work at high temperatures 100-450 °C [29, 48]. The fundamental sensing mechanism of metal oxide-based gas sensors is based on a shift in the equilibrium of the surface chemisorbed oxygen reaction, due to the presence of the target gas. Based on the sensitive material type, MOS can be divided into *n*-type and *p*-type, which exhibit different sensing behaviors to the same gas being detected. Upon exposure to oxidizing gases, the gas species acts as an acceptor, leading to a resistance increase for the *n*-type semiconductor, and a decrease for the *p*-type semiconductor. As for the reducing gases, the gas species acts as a donor, leading to a resistance decrease for the *n*-type semiconductor, and an increase for the *p*-type semiconductor. Commonly, a double Schottky barrier model is utilized to specifically explain the details of the MOS gas sensor mechanism, as shown in Fig. 2b. For the *n*-type MOS gas sensor, oxygen is adsorbed in the grains from the air, to attract electrons from the grains for forming oxygen species (O , O_2), hereby inducing an electron-depleted layer to increase the surface potential. Thus, a potential barrier is formed between the adjacent grains, which hinders the migration of electrons from one grain to another. After the exposure to reducing gases, the oxygen species are consumed, leading to a decreased in the

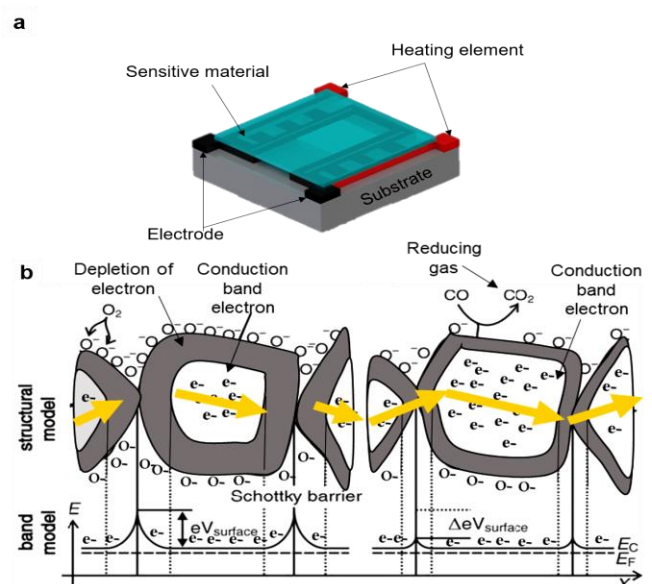


Fig. 2. (a) Schematic design of a metal oxide semiconductor gas sensor. (b) Mechanism of *n*-type MOS gas sensor in double Schottky barrier model.

Table I
PERFORMANCE COMPARISON OF VARIOUS MOS GAS SENSORS AND SENSITIVE MATERIALS

Ref.	Sensitive Material	Gas Sensing	Working Temperature (°C)	Fabrication Technique	Detection Range	Response Time (s)	Recovery Time (s)	Sensitivity
[30]	Polyhedral ZIF-8 nanostructures	Nitrogen dioxide (NO ₂)	350	Solvothermal method.	10–100 ppm	113.5	111.5	118.5 Ra/Rg
[31]	ZnO pyramid	Isoprene (C ₅ H ₈)	300–350	Solvothermal method	1 ppm	N/a	1800	1371 Ra/Rg
[32]	SnO ₂ nanoparticle	Ethanol (C ₂ H ₅ OH)	400	PECVD	1–25 ppm	17.6	16.7	29.7 Rg / Ra
[33]	ZnO doped indium oxide	NO ₂	167	SILAR method	0.1–100 ppm	180	N/a	24.2 Rg/Ra
[34]	PANI/Cellulose/WO	Acetone (C ₃ H ₆ O)	Room temperature	Drop-casting	10–100 ppm	N/a	N/a	N/a
[35]	CuO nanoribbon	C ₂ H ₅ OH	Room temperature	Wet chemical	100 ppm	2	N/a	N/a
[36]	Indium doped ZnO	C ₂ H ₅ OH	360	Spray pyrolysis	100 ppm	15	60	75 Rg/Ra
[37]	Pt / (NiO)	Tropene	Room temperature	N/a	N/a	37.2	38.3	N/a
[38]	CuO nanowire	C ₂ H ₅ OH	Room temperature	Thermal oxidation	10 ppm	202	198	N/a
[39]	In ₂ O ₃	NO ₂	130	CVD	50 ppb	N/a	N/a	N/a
[40]	TiO ₂	Ammonia (NH ₃)	350	Hydrothermal process	56,103,156 ppm	N/a	N/a	1 Ra/Rg
[41]	Platinum doped TiO ₂	Hydrogen (H ₂)	500–800	Dipping method	N/a	40	N/a	N/a
[42]	Aluminium-doped titanium dioxide (TiO ₂) nanopowder	Co	600	Combustion method.	100–500 ppm	N/a	N/a	N/a
[43]	TiO ₂ nanoparticle	Co	500	Drop-coating method	1–75 ppm	30–60	550	N/a
[44]	Platinum (Pt) doped (SnO ₂) nano particle	Co	350	In-situ deposition	8–50 ppm	N/a	N/a	N/a
[45]	TiO ₂ nano particle	Methanol (CH ₃ OH)	375 – 475	Spin coating	50 ppm	4	30	N/a

potential barrier height, which is beneficial for electron transport between grains. This will lead to a decrease in the resistance of the MOS sensor. In general, the performance of a gas sensor is measured by its sensitivity and recovery time (defined as the time required to reach 90 % of the final equilibrium value). The sensitivity of a gas sensor can be divided into two types, depending on the type of material (*n*-type material or *p*-type material), whereby, both have the necessary resistance required for gas sensors in the reference gas, *R_a*, and the resistance of the gas sensor in the target gas, *R_g*. Sensitivity levels are shown in Table I and it can be defined as *R_a/R_g* for the reducing gases, which are utilized in *n*-type materials. The *p*-type materials use the *R_g/R_a* for oxidizing gases [46].

To improve the performance of the MOS gas sensor, some researchers focused on sensing materials. There are a few commonly used sensitive materials for MOS gas sensors, such as zinc oxide (ZnO), titanium dioxide (TiO₂), ferric oxide (Fe₃O₂) and tin (IV) oxide (SnO₂) [35,40]. However, SnO₂ is found to be the most widely used sensitive material for this type of gas sensor among the available sensitive materials, due to its stability towards reducing gases. Several researchers synthesized this material in nanostructure form, because it provided a much larger surface area, and improve the

sensitivity of the MOS gas sensor. Table I indicates that Chen et al [32] developed SnO₂ nanoparticles which showed a high level of sensitivity (29.7 Rg/Ra), as compared to other sensitive materials for detecting ethanol. The response was recorded fairly quickly, reflecting its efficiency in the process. Some researchers have also shown that metal oxide doping of nanomaterials could improve the response and recovery time of MOS sensors. Liu et al. used Indium oxide doping with molybdenum disulfide nanocomposites which recorded a fast response (8 s) and recovery time (20 s) [47]. Most of the MOS-based sensors are known to be stable, safe, low cost, and sensitive in detecting VOC gases. Therefore, they have become a paramount technology in commercial, domestic, and industrial gas-sensing systems [48]. However, MOS sensors have one obvious limitation, that is their high-power consumption due to the high operating temperature, ranging from 150–400 °C [29, 48]. This limitation was overcome with the innovation of the chemiresistive gas sensor, which was introduced by Seiyama, which did not require a heater in the gas sensor. This gas sensor is briefly discussed in the next section.

2) Chemiresistive Gas Sensors: Five decades ago, Seiyama introduced the chemiresistive gas sensing technology using ZnO thin film for propane detection and the sensitivity was

100 times higher than the thermal conductivity detector, which was commonly used at that time [28]. This significant development enhanced the use of chemiresistive gas sensors until recent years, achieving an optimum state of continuous development. A chemiresistive gas sensor is an electrochemical sensor that operates due to the changes in the material's electrical resistance, from the reactions on the surface of the sensing element. Compared to MOS sensors, chemiresistive gas sensors have a simple design without the use of a micro-heater. Normally, the basic structure of a chemiresistive gas sensor consists of two electrodes and sensitive materials in the middle (Fig. 3a), which is enabled using a simple fabrication process utilizing these film materials. The sensor can also be realized on polymer substrates using flexible chemiresistive gas sensors, as shown in Fig. 3b. When the chemiresistive sensor is exposed to the target gas, the gas molecule interacts with the sensing material, which causes a change in the resistance.

Several materials have been used as sensing materials for chemiresistive gas sensors, such as conductive polymers, metal oxides, and nanostructured materials [49, 50]. In recent studies, most of the researchers utilized nanostructured materials for sensing. Studies have proven that a nanomaterial's sensing properties can be dramatically affected by the morphology and structure of the sensing material. This was shown by Sonalika Agarwal et al., where two kinds of nanostructured ZnO in the form of nanostructured flowers and nanorods were synthesized using a hydrothermal method [51]. The results showed that the nanoflower structure had much higher sensitivity compared to nanorod structures, due to its larger surface area [51]. According to Zhang et al., doping methods can be utilized to further improve the sensitivity of chemiresistive gas sensors [42, 52, 53]. Le et al. adopted a doping technique to synthesize SnO₂ and RGO using the hummer method [54]. A sensitivity of 11.8 Rg/Ra was recorded in 110 ppm of NO₂. Similarly, Dixit et al. also developed a Fe-Al and PANI thin film using a doping and vacuum deposition method and obtained a high 800 Rg/Ra in a low ppm (10 ppm) of CO [55]. However, some doping methods can improve the sensitivity of the gas sensor, but it also increases the response and recovery time, which is not

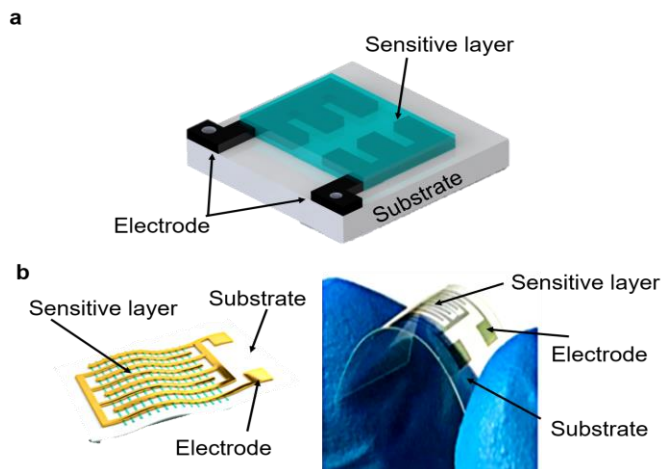


Fig. 3. (a) Schematic design of a chemiresistive gas sensor. (b) Flexible chemiresistive gas sensor. Reprinted from [100], Copyright (2019), with American Chemical Society.

preferred in gas sensors. Table II shows the performance of the gas chemiresistive sensors using various sensitive materials. Most of these chemiresistive gas sensors have been employed in real-time environmental monitoring due to their simple structure, low power consumption, and high sensitivity to toxic gases [18]. Nonetheless, one of the major issues with chemiresistive sensors is the sensing material, which is affected by humidity, which eventually affects the sensitivity of the sensor [56, 57]. To overcome this limitation, researchers investigated other MEMS sensors, such as optical and acoustic gas sensors, which are discussed in the following sections.

B. Optical Gas Sensor

Many different optical gas-sensing techniques have been commercialized, and they play an important role in a wide range of industries and applications. Photonic crystal cavity (PhC) gas sensors and fiber-optic gas sensors are two of the regularly used MEMS optical gas sensors. This section will review PhC and fiber optic gas sensors in detail.

1) *Photonic Crystal Cavity (PhC)*: PhC is a material with periodicity in the dielectric constant, which was proposed in 1987 by Yablonovitch and John [58, 59]. These materials affect the photon motion in the same way that electron motion is affected by the semiconductor crystal [60]. The photonic bandgap (PBG) is produced by arranging the dielectric material within the PhC. Light at certain frequencies or wavelengths located in the PBG is prohibited from propagating through the PhC, while other light wavelengths are permitted to do so [59, 60]. This results in the ability of PhC to control light and produce effects that are impossible with conventional optics. In the development of the PhC gas sensor application, the quality factor (Q) and sensitivity (S) are considered as the main characteristics. Q is proportional to the energy stored inside the cavity structure, whereas the mode volume is related to the size of the cavity. There are three types of PhC gas sensors: 1D, 2D, and 3D configurations. The 3D configuration structure has limited applications, and the fabrication process is complicated [61]. Most researchers tend to develop the 2D configuration, as shown in Fig. 4a, because it has a higher Q than other configurations. As shown in Fig. 4b, the PhC is placed between the light source and the detector. The mechanism of the PhC gas sensor can be described using Bragg's law (1) [60]:

$$m\lambda = 2nd \cdot \sin\theta \quad (1)$$

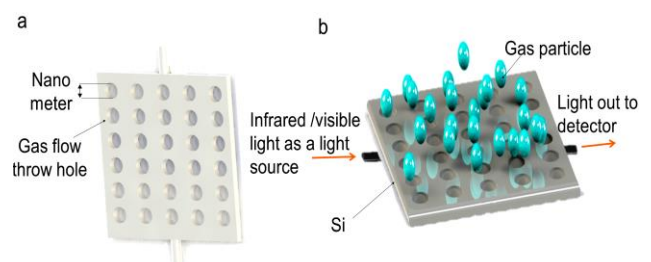


Fig. 4. (a) Schematic view of a photonic crystal gas sensor. (b) Mechanism of a PhC gas sensor.

Table II
SUMMARY OF CHEMIREISTIVITIVE GAS SENSORS PERFORMANCE

Ref.	Sensitive Material	Gas Target	Working Temperature (°C)	Fabrication Method	Detection Range	Response Time (s)	Recovery Time (s)	Sensitivity
[49]	Polystyrene/Polyaniline core-shell	CH ₂ O	Room temperature	Drop-casting	1-50 ppm	5 min	30 min	37.6 Rg/Ra.
[50]	SnO ₂ /NiO nanocomposites	NO ₂	230	Hydrothermal method	20 ppm	N/a	N/a	14.45 Rg/Ra.
[14]	PPy thin film	NH ₃	Room temperature	Polymerization process	4-80 ppm	20 s	15 min	1.12 Rg/Ra.
[62]	PPy nanofiber	NH ₃	Room temperature	Reactive template approach	20-150 ppm	15 s	N/a	1.53 Rg/Ra.
[63]	PPy film	CH ₃ OH	Room temperature	Chemical oxidative method	-	150 s	400 s	1.05 Rg/Ra.
[29]	PPY nanowire array	H ₂	Room temperature	Chemical polymerization	1300-12000 ppm	692 s	1396 s	1.01 Rg/Ra.
[38]	Ag-doped ZnO nanowire	H ₂	Room temperature	Electrodeposition	100 ppm	22 s	11 s	N/a
[64]	PPy thin film	No ₂	Room temperature	Spin coating technique	10-100 ppm	126 s	2170 s	1.12 Rg/Ra.
[65]	Iodine doped polythiophene (PTh) film (IPTF)	NH ₃	Room temperature	Electrophoretic deposition technique	460–1850 ppm	78 s	346 s	1.95 Rg/Ra.
[66]	Polythiophene-SWNTs	No ₂	Room temperature	Potent ion static deposition	10 ppb - 10 ppm	20 s	N/a	28 Rg/Ra.
[67]	MWCNTs/ ZnO composite	CH ₄	Room temperature	N/a	500 ppt-10ppm	20 s	N/a	2.3 Rg/Ra.
[55]	Fe-Al doped PANI thin film	CO	Room temperature	Vacuum deposition	10–150 ppm	5 s	10 s	800 Ra/Rg
[68]	ZnO/ ZIFs -CoZn	C ₃ H ₆ O	250	Drop-casting	0.25-100 ppm	0.72 min	1.02 min	27.5 Ra/Rg
[69]	ZnO/ZIF-8 nanowire	CH ₂ O	300	N/a	100 ppm	30 s	120 s	12.5 Rg/Ra.
[54]	SnO ₂ /rGO	No ₂	55	Hummers method	14 -110 ppm	80 s	380 s	11.8 Rg/Ra.
[70]	ZnO/Pd/ZIF-8 nanowires	H ₂	200	N/a	10 -50 ppm	N/a	8.33 s	6.7 Rg/Ra.
[71]	Al-doped ZnO	CO	300	Sol-gel technique	50 ppm	7 s	30	1.6 Rg/Ra.
[72]	Tantalum pentoxide (Ta) alloyed In ₂ O ₃	No ₂	120	RF magnetron sputtering	100 ppm	59 s	339 s	64.5 Rg/Ra
[73]	Ta alloyed In ₂ O ₃ rod array	No ₂	110	RF magnetron sputtering	100 ppm	48 s	329 s	76.1 Rg/Ra

where m is the diffraction order, λ is the wavelength of the incident light, n is the effective refractive index of the periodic structure, d is the spacing between the planes in a lattice, and θ is the glancing angle between the incident light and diffraction planes. Assuming that $\sin\theta$ is fixed when the gas particles pass through the PhC and the spacing of the lattice distance, d , on the PBG are changed.

Thus, both changes in the refractive index and the lattice distance can affect the resultant diffraction wavelength of the incident light, thus enabling the detection of gases in the PhC gas sensor [60]. PhC materials can be fabricated by using either a self-assembly technique or an advanced MEMS technique, such as e-beam lithography [74] or chemical vapor deposition (CVD) [75, 76]. The dimension and shape of the PhC can be controlled accurately using MEMS fabrication methods. PhC can be fabricated using self-assembly techniques by utilizing chemical and physical methods, where nanoparticles are produced by annealing thin metal films arranged along with the substrate's crystallographic orientation [78]. This technique is much simpler and cheaper than MEMS methods but can induce a defect in the resultant PhC structure [75].

Some of the clad portions are generally close to each other. Photo crystal gas sensors have high sensitivity, stability

toward environmental factors, and a much longer lifetime. However, limitations still appear in the miniaturization of PhC based gas-sensing devices, due to the size of an external light source and photodetector. As shown in Table III the performance of the PhC gas sensor over the past few years managed to prove that the 2D configuration is much widely reported than the 1D configuration. The 2D configuration has been widely studied as a gas sensor because of its higher Q factor and higher sensitivity [77].

2) *Fiber-Optic*: Since the invention of the optical fiber endoscope in the first half of the 20th century, the fiber optic sensor has made significant progress in the field of gas sensing [79]. Fiber optic gas sensors have attracted researcher's attention due to their sensing characteristics, and their ability to monitor toxic gases. Essentially, the fiber optic sensors consist of a sensing region, core, and a clad, as shown in Fig. 5a. If the refractive index of an outer layer is smaller than the inner core of the fiber optic, the light will sense total internal reflection and propagate only in the core [80]. On the other hand, if the cladding and core refractive index values are close, the light will be propagated, resulting in the clad region's penetration. In the fabrication of optical fiber gas sensors, the cladding and the core refractive index must be removed and a sensitive layer with an extensive refractive

Table III
SUMMARY OF PHOTONIC CRYSTAL CAVITY GAS SENSORS PERFORMANCE

Ref.	Substrate Material / Sensitive Material	Periodic Dielectric Structures	Gas	Quality Factor	Detection Limit (RIU)	Sensitivity (nm/RIU)
[81]	Silicon-on-insulator (SOI) Tungsten oxide	2D	H ₂ S	3×10^3	2.08×10^{-7}	2.3×10^{-5}
[82]	Silicon slab/Cryptophane E	2D	Methane (CH ₄)	14,717	N/a	614
[83]	SOI/Graphene	2D	H ₂ S	N/a	1.87×10^{-7}	1.2×10^6
[84]	Silicon slab/ Cryptophane E molecular	2D	CH ₄	1105	1.00-1.20	45
[85]	Si/ N/a	2D	Acetylene and H ₂	4459	N/a	388
[86]	SOI /Cholesteric liquid crystal	2D	THF vapor	2×10^5	4×10^{-5}	194
[87]	SOI/Lead (Pb)	2D	Hexane (C ₆ H ₁₄) and C ₃ H ₆ O	7500	2.3×10^5	370
[88]	SOI/ N/a	2D	Organic vapor	26×10^4	1×10^{-5}	510
[89]	Si / Air layers	1D	N ₂ , He, CO ₂ Sensing	N/a	N/a	1200
[90]	Si/ Magnesium fluoride (MgF ₂)	1D	CH ₄ and Ethane	3×10^5	10^{-5}	700

index deposited onto it to form the modified clad layer. As a result, a gas sensing interface occurs in the modified clad and gas. In the presence of target gases, the optical properties of this modified cladding layer will be changed, and as a result, the refractive index of the sensing layer will be modified [91]. This technique enables the detection of small changes in light associated with the light pulse amplitude and fall time. Due to the simplicity of this mechanism, many configurations have been designed to improve the sensitivity of fiber optic gas sensors. In Fig. 5, recent types of fiber optic gas sensors such as fabry perot [92] (Fig. 5b), photonic crystals [93] (Fig. 5c), evanescent waves [94] (Fig. 5d), and surface plasma resonance [95] (Fig. 5e) are shown. Many researchers have reported evanescent wave types as a fiber optic gas sensor, because of its sensitivity and simplicity of fabrication [96]. In general, the fiber-optic gas sensor is made by removing some cladding portions, followed by the deposition of the sensing material on the removed cladding. For advanced structures such as fabry perot or fiber bragg grating type, fabrication methods such as electronic arc discharge [97], femtosecond (fs) laser micromachining [98], and wet etching [99], can be used to control the length interference of the fiber optic. The sensitive material deposition of fiber optic gas sensors is dependent on the type of sensitive material, such as the metal oxide and polymers. For metal oxide, the hydrothermal method and thermal evaporation technique have been used [101]. In the case of a polymer sensing layer, the polymer film is first dissolved in a solvent and then deposited on the optical-fiber sensitive region via drop-casting, spray coating, dip coating, or spin coating [102]. Due to their highly tunable physicochemical properties, high conductivity, and cost-effectiveness, sensing materials such as SnO₂, Sm₂O₃, Bi₂O₃, ZnO, and WO₃ have been extensively used on the modified clad of the metal oxide optic gas sensors. The use of nanostructured sensing materials in fiber optic gas sensors have resulted in improved sensing performance.

For instance, Subramanian et al. developed a sensor using zinc vanadate (Zn₃(VO₄)₂) nanopowder to detect ammonia gas, which showed a higher sensitivity of 0.019 $\mu\text{V ppm}^{-1}$ [103]. However, the response time (46.8 min) and recovery

time (59 min) recorded were relatively higher. Similarly, Zhu et al. used a ZnO nanoflower sensing material employed sensor and obtained a short response time (26 s) and recovery time (36 s) [104]. Table IV shows the performance of gas fiber optic sensors using various sensitive materials. It demonstrates that the doped method used by the researchers can improve the sensitivity, recovery, and response times of the fiber optic gas sensors. This is due to the fact that the dopant acts as catalyst, causes structural changes, and may introduce electronic energy bands, all of which improve the gas sensing properties in the fiber optics [105]. For instance, Shanavas et al. demonstrated that NiO doped rGO nanocomposites provided a high sensitivity of 83 Count/kPa, with a short time response time (16 s) and recovery time (22 s) when detecting CO₂ gas [106]. Although, fiber-optic gas sensors have several advantages over other optical gas sensors, including high

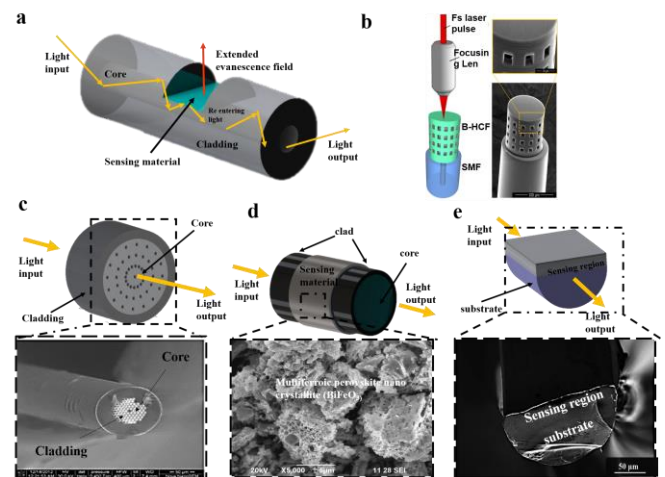


Fig. 5. (a) Schematic view of a typical fiber optic gas sensor. (b) Fabry perot interferometer. Reprinted from [92], Copyright (2021), with permission Elsevier. (c) Photonic crystal. Reprinted from [93], Copyright (2016), with permission Elsevier. (d) Evanescent waves. Reprinted from [94], Copyright (2021), with permission Elsevier. (e) Surface plasma resonance. Reprinted from [95], Copyright (2021), with permission Elsevier.

Table IV
SUMMARY OF FIBER OPTIC GAS SENSORS PERFORMANCE

Ref.	Material	Gas Target	Working Temperature (°C)	Fabrication Method	Detection Range	Response Time (s)	Recovery Time (s)	Sensitivity (Counts/kpa)
[107]	Bismuth tungstate (Bi ₂ WO ₆) nanomaterials	NH ₃	Room temperature	Hydrothermal technique	0-500 ppm	N/a	N/a	5
[106]	NiO doping with reduced graphene oxide(rGO) composite	CO ₂	Room temperature	Irradiation technique	0-500 ppm	16	22	83
[107]	Bismuth tungstate (Bi ₂ WO ₆) nanomaterials	CH ₃ OH	Room temperature	Hydrothermal technique	0 to 500 ppm	N/a	N/a	122
[106]	NiO doping with rGO composite	Acetone	Room temperature	Irradiation technique	0-500 ppm	20	27	N/a
[108]	Molybdenum disulfide (MoS ₂) doping graphene	No ₂	Room temperature	Chemical method	0-500 ppm	22 s	35 s	61 %
[109]	Cadmium sulfide (CdS)	H ₂	Room temperature	Chemical bath deposition	0-700 ppm	10 min	N/a	63.4 % at 600 ppm
[110]	ZnO nanorods	H ₂	Room temperature	Growth solution	N/a	7 min	3 min	N/a
[111]	(a) ITO film and nanoparticles (b) ITO nanoparticles (c) ITO film	H ₂	Room temperature	Thermal evaporation technique, dip coating for nanoparticle	0-100 ppm	1 min	N/a	a) 0.71 (b) 0.58 (c) 0.2 nm ppm ⁻¹
[103]	Zinc vanadate (Zn ₃ (VO ₄) ₂) nanopowder	NH ₃	Room temperature	Dip coating	20-500 ppm	46.8 min	59 min	0.019 μ V ppm ⁻¹
[104]	Three-dimensional ZnO nanoflowers	NH ₃	Room temperature	Drop coating	0-7281 ppm	26 s	36 s	4.32 counts ppm ⁻¹
[112]	Nanostructures Manganese nitrate/Cobalt nitrate/Urea/Liquid ammonium hydroxide solution (MnCO ₂ O ₂)	C ₂ H ₅ OH	Room temperature	Drop coating	0-500 ppm	11 min	45 min	-0.55 counts ppm ⁻¹
[112]	MnCO ₂ O ₂ nanostructures.	C ₃ H ₆ O	Room temperature	Drop coating	0-500 ppm	70 min	55 min	-0.068 counts ppm ⁻¹
[113]	(a) ZnO thin-film ZnO nanoparticles, (b) ZnO nanoparticles (c) SPR (silver ZnO)	H ₂ S	Room temperature	Thermal evaporation technique and nanoparticles dipping	10-100 ppm	N/a	N/a	(a) 1.49, (b) 1.06 and (c) 0.24 nm ppm ⁻¹
[101]	Nanocrystalline samarium oxide Sm ₂ O ₃	C ₂ H ₅ OH	N/a	Dip coating	0-500 ppm	78 min	71 min	76 (10 ⁻³ /kPa)
[114]	GO	CH ₃ OH	27	Chemical oxidation process	0-500 ppm	N/a	N/a	-0.20 counts ppm ⁻¹
[115]	rGO	CH ₃ OH	27	Hummers method	0-500 ppm	N/a	N/a	0.0038 counts ppm ⁻¹
[116]	Multi-walled carbon nanotubes (MWCNTs)	CH ₃ OH	Room temperature	N/a	0-500 ppm	N/a	N/a	0.14 counts ppm ⁻¹

sensitivity, selectivity, and stability [102], however, it has limitations in terms of miniaturization of the light source and photodetector [117]. It is also easily affected by ambient light interferences. Because of this limitation, researchers have continued to optimize the fiber optic gas sensor, and some of the researchers have explored acoustic gas sensors instead. Acoustic gas sensors are explained in detail in the next section.

C. Acoustic Gas sensors

Acoustic wave gas sensors get their name from the fact that they use a mechanical, or acoustic, wave to detect gases [118].

The acoustic sensor provides a much better gas sensing performance because of the ensuing interactions, which can be even detected at lower gas concentration levels [119]. A major problem with acoustic sensors is the limited selectivity related to the common sensing materials used. Several MEMS acoustic gas sensors have been investigated, including the quartz crystal micro-balance (QCM) and SAW sensors.

1) Quartz Crystal Microbalance Gas Sensors: In 1959, Sauerbrey et al. claimed that the change in the frequency of the quartz resonator was in direct proportion to the increased mass and had proposed the Sauerbrey equation [120]. Since

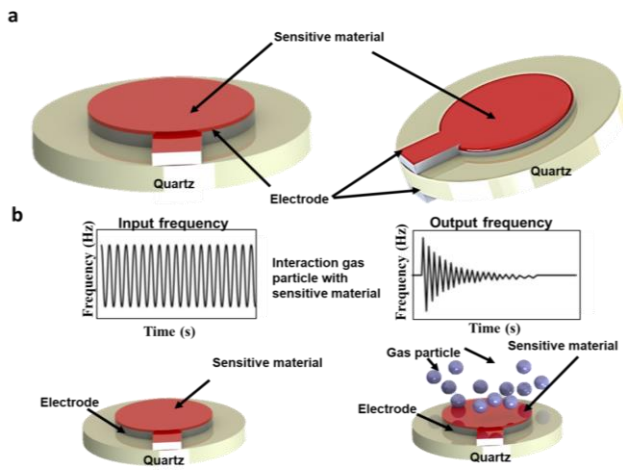


Fig. 6. (a) Schematic design and (b) Working mechanism of a QCM gas sensor.

then, quartz crystals are used in many applications, including gas sensors. Fig. 6a shows the basic QCM gas sensor, which is made up of a sandwiched quartz crystal between two electrodes, and a sensing material deposited onto the top of the sensing electrode [121]. The basic mechanism of the QCM can be explained using Sauerbrey equation [120] refer in equation (2).

$$\Delta f = \frac{2 f_0^2}{\sqrt{\rho_q u_q}} \frac{\Delta m}{A} \quad (2)$$

where, Δf and Δm are the quartz's resonance frequency shift (Hz) and mass change (gm) related to the surface adsorption of the QCM, respectively; f_0 is the fundamental frequency of the quartz (Hz); A is the active area of the QCM rigid film on the electrode (cm²); ρ_q and u_q are the density (g/cm³) and shear modulus (Pa) of the piezoelectric quartz crystal, respectively. QCM gas sensors detect the sensing layer's mass change by measuring the quartz's resonance frequency shift, as shown in Fig. 6b. When the gas is released, the sensitive material's molecule will absorb the target gas. Thus, a mass variation, Δm , is induced. This is followed by a decrease in the quartz's resonance frequency. Usually, the frequency is generated by the QCM sensor, which ranges from 5 to 10 Mhz [122], whereby, the generated frequency depends on the thickness of the quartz [123]. The lower the thickness of the quartz, the higher the frequency. In general, quartz crystal itself does not have gas-sensing properties, and it is difficult for the gas molecules to be directly combined with the metal electrode. Therefore, the surface of the QCM needs to be coated by a thin film of gas-sensitive materials with adsorption properties, so that the adsorption between the target gas and sensing material occurs [124]. The QCM gas sensors sensing materials such as metal oxides and polymers can be prepared using physical and chemical methods, such as precipitation [125], gel [126], hydrothermal [127, 128], microemulsion [129], and solvent solutions [130]. In recent studies, most researchers used nanostructure materials as QCM sensitive materials because of their advantageous features, such as a very high surface to volume ratio, and high sensitivity. This was shown in Yang et al.'s study on three types of CuO nanostructures as

QCM gas sensors. They reported that the higher surface area (9.3 m²/g) is much more sensitive than a lower CuO nanostructure area (1.5 m²/g) [131]. Table V shows the performance of the QCM gas sensors over the last decade. NH₃ and CO gases have been widely been reported as QCM sensing gases for working at room temperatures. The shortest time response was reported by Wang et al. for NH₃ detection using a ZnO nanowire as the sensing material [132]. However, a slower response time (720 s) was reported by Minh et al. [133]. For CO gas detection, a high sensitivity of 108.85 Hz/ppm was reported by Bayram et al. using a ferrocene doped chitosan material [134]. QCM based acoustic gas sensing offers advantages, such as a smaller device size, and higher sensitivity for the detection of toxic gases. On the contrary, QCM gas sensors have a few limitations such as complex fabrication processes, low signal to noise ratio due to the crystal's surface interference, and it is much less sensitive than the SAW sensors [118]. Found an easy way to generate surface acoustic waves in the piezoelectric material using described the surface acoustic.

2) Surface Acoustic Wave Sensors (SAW): Surface acoustic waves were first explained in 1885 by Lord Rayleigh, who described the surface acoustic mode of propagation in the piezoelectric material [135]. Later on, White and Voltmer found an easy way to generate surface acoustic waves in the piezoelectric material using interdigital transducers (IDT) [136]. The basic structure of the SAW gas sensors consists of a piezoelectric substrate, input and output IDT, a sensitive material in the middle of the SAW sensor, and a pair of reflectors (Fig. 7a). Since then, SAW sensors have played an important role in a comprehensive range of applications, including gas sensors. SAW gas sensors have been widely used in biomedical applications for the monitoring of VOC gases. In general, the surface acoustic waves are stimulated by applying a sinusoidal wave to the IDTs which are deposited on the piezoelectric material. Due to the piezoelectric effect, electric fields will cause alternating regions of tensile and compressive strain between the IDT fingers, and produce a mechanical wave at the surface (Fig. 7b). comparing the changes in the frequency of the output and input signals. The reflector on a SAW gas sensor is designed to reduce insertion losses and prevent interference patterns in the SAW sensor [137]. The piezo substrate itself does not have gas-sensing properties. Hence, the surface of the delay line (area in between the input and output IDT) needs to be coated with a

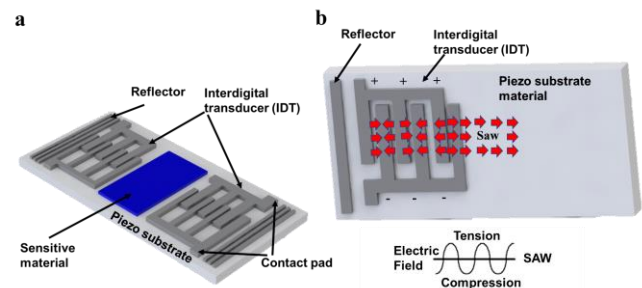


Fig. 7. (a) Schematic diagram and (b) Working mechanism of a SAW gas sensor.

TABLE V
SUMMARY OF QCM GAS SENSORS PERFORMANCE

Ref.	Material	Gas	Working Temperature (°C)	Fabrication Method	Time Response	Recovery Time (s)	Detection Range	Sensitivity
[132]	ZnO nanowires	NH ₃	Room temperatures	Drop-coating technique	4-5 s	N/a	1000 ppm	- 956 Hz/ ppm
[138]	Polyaniline/Graphene	NH ₃	Room temperatures	Drop-coating method	50 s	23 s	100 ppm	3.65 (20 ppm), 11.33 (100 ppm)
[133]	ZnO nanorods	NH ₃	Room temperatures	Hydrothermal method	720 s	1400 s	800 ppm	85 Hz/ ppm
[139]	Polyaniline/GO layer	NH ₃	Room temperatures	Drop-coating method	79 s	3 s	800 ppm	214 Hz/ ppm
[140]	CA/PEI/GO nanofiber	NH ₃	Room temperatures	Sol-gel method,	<10 s	N/a	80 ppm	11.3 Hz/ ppm
[141]	ZnO nanorods	CO	Room temperatures	Wet chemical route	N/a	N/a	150 ppm	$\Delta f = 0.62$ Hz/ ppm
[142]	Poly(styrenesulfonate)/polyvinylpyrrolidone (PEDOT:PSS/PVP)	CO	Room temperatures	Traditional electrospinning	N/a	N/a	50 ppm	$\Delta f = -54$ Hz/ ppm
[143]	Vanadium oxide	CO	Room temperature	Thermal evaporating method	N/a	N/a	N/a	$\Delta f = -17.5$ Hz/ ppm
[134]	Ferrocene-chitosan	CO	Room temperature	Drop-casting method	38 s	64 s	0-2000 ppm	$\Delta f = 108.85$ Hz/ ppm
[144]	Cryptophane-A	CO	80	Electrospray method	N/a	N/a	N/a	0.004 Hz/ppm
[145]	Indium-Tin oxide	No	Room temperature	Spin-coating	N/a	N/a	1000 ppm	0.12 Hz/ppm

gas-sensitive thin film material which has adsorption properties, so that the adsorption between the target gas and sensing material occurs [146]. By contrast, other researchers have claimed that, by employing a layered structure on a SAW sensor, it is possible to increase the gas sensor's sensitivity. The mechanical wave of the SAW sensor will be propagated in both directions from the input IDT, and invoke a modulation of the acoustic wave, which can be determined via frequency shift of the sensor. This study was conducted by Ippolito et al [147], which showed that the layered SAW sensing layer had higher sensitivity compared to the non-layered material. Table VI shows the performance of the SAW sensor over the past decade. Metal oxide/nanostructures [148], polymer-based sensors [149, 150], novel materials [150] and semiconducting crystals [151], have been reported as sensing materials for the detection of NH₃, CO and H gases. SAW gas polymer-based sensors are widely reported because polymers provide faster responses and higher sensitivity to toxic gases for gas sensing [149]. For Instance, Lin et al. demonstrated that a SAW Sensor based on Poly-N-vinylpyrrolidone (PNVP) had a higher sensitivity (27.5 Hz/ppm) and faster response time (40 s) for sensing NH₄ gases [152]. To improve the SAW gas sensor, some researchers proposed polymer-based doping with metal oxides to improve the sensitivity, response, and recovery time. In a study by Sadek et al., polyaniline doped tungsten trioxide nanofibers were utilized [153]. In this work, a sensitivity of 7 kHz/ppm, the response time of 40 s, and recovery time of 1.2 s was recorded for sensing 100 ppm of hydrogen gas. In another work using a similar method, Setka et al. developed a SAW-based on Au doping with PPy, which showed a sensitivity of 898 Hz/ppm, with a response time of 59 s, and a recovery time of 72 s for detecting 10 ppm of NH₃ [154]. However, the polymer deposition on the SAW sensor has disadvantages, such as high losses, and low propagation

velocity due to humidity [118, 119]. Every gas sensor has its limitations and advantages. SAW gas sensors are known for their higher sensitivity, short detection time, and smaller device size [120]. SAW sensors also operate at higher frequencies than other acoustic-type gas sensors, and this contributes to its higher sensitivity. The limitations of the MEMS SAW gas sensors are their high fabrication costs and the need for advanced equipment for the fabrication process.

III. GAS SENSOR IN BIOMEDICAL APPLICATION

Gas sensors are widely used in medical applications to diagnose diseases by analyzing human breath. Human breath, in general, contains oxygen, carbon dioxide, nitrogen, inert gases, and numerous trace-level biomarkers related to disease diagnosis. The exhaled biomarkers correspond to specific diseases of different organs, typically NH₃ for renal disease, NO for asthma, acetone for diabetes or body fat monitoring, and VOC gas for lung cancer. However, only a few breath measurement sensors have been applied in clinical practice. Exhaled NH₃ can be used as a diagnostic biomarker for renal disease diagnosis [167]. Typically, exhaled NH₃ concentrations for a healthy person is about 0.425-1.8 ppm, while that of an end-stage renal disease (ESRD) patient is around 0.82-14.7 ppm [167]. Wu et al. developed a flexible NH₃ gas sensor based on GP-PANI/PVDF nanocomposites, as shown in Fig. 8a, to diagnose kidney failures [23]. In his research, he reported a 60 % response to 1 ppm NH₃ and had a remarkable response time (46 s) and recovery time (198 s). Similarly, Yu et al. successfully developed a gas sensor to analyze kidney failures for patients based on TFB as sensitive material, as shown in Fig. 8b. Using this material, a sensitivity of (-0.52 % to 31.81 %) was recorded for 100 to 5600 ppb [24]. Abbaszadeh et al. developed an optical gas

TABLE VI
SUMMARY OF SAW SENSORS PERFORMANCE

Ref.	Sensitive Material	Gas	Working Temperature (°C)	Deposition Method	Working Frequency (MHz)	Detection Range	Response Time (s)	Recovery Time (s)	Sensitivity
[157]	Cellulose nano-crystals (CNCs)	HC	Room temperature	Spin-coating method	200	1 -10 ppm	~45 s	~500 s.	-2 kHz/ppm
[158]	Palladium (Pd)/ Copper (cu) nanowire	H ₂	Room temperature	Optimized electrochemical deposition	150	100 ppm	4 s	4 s	1.5 kHz/ppm
[159]	Ca ZnO thin film coated LGS	CO	400	Spin coated	7.89	1000 ppm	87 s	132 s	2.469 kHz/ppm
[160]	ZnO nanowires	H ₂	Room temperature	Pulsed laser deposition (PLD) technique	69.5	2117 ppm	9 s	15 s	0.015 Hz/ppm
[161]	Pd/ ZnO	H ₂	Room temperature	Pulsed laser deposition technique	69.5	59 ppm	12 s	16 s	0.51 Hz/ppm
[162]	(Pd) surface modified SnO ₂	H ₂	275	RF-magnetron sputtering	100	100-2000 ppm	<24 s	10 min	115.9 kHz/ppm
[163]	Polyaniline/In ₂ O ₃	H ₂ , CO and NO ₂	Room temperature	Drop casting	107.2	N/a	30 s	40 s	11 kHz/ppm
[149]	Au/PPy	NH ₃	Room temperature	Spin coating	N/a	2 -10 ppm	59 s	72 s	898 Hz/ppm
[164]	ZnO nanofilm	NH ₃	Room temperature	sol-gel and spin-coating	199.89	100 ppm	143 s	426 s	-0.307 Hz/ppm
[164]	ZnO NRs	NH ₃	Room temperature	Hydrothermal method	199.76	100 ppm	151 s	568 s	-1.094 Hz/ppm
[165]	l-glutamic acid hydrochloride	NH ₃	Room temperature	Air brushed coating.	100	<4.0 ppm	<5 min	< 3 min	74 Hz/ppm
[166]	ZnO/SiO ₂ (ZCS) composite film	NH ₃	Room temperature	Sol-gel method and spin-coated	198.8	50 ppm	N/a	N/a	0.02264 kHz/ppm
[168]	ZnS nanostructures	NH ₃	Room temperature	Chemical bath deposition method	200	20 ppm	45 s	148 s	62.5 Hz/ppm
[169]	Colloidal quantum dots (CQDs)	NO ₂	Room temperature	Drop casting	200.02	10 ppm	180 s	446 s	180 Hz/ppm
[170]	ZnO	NO ₂	Room temperature	RF magnetron sputtering	99.5	0.4 ppm	N/a	N/a	6.0 kHz/ppm
[171]	Lead zirconate titanate (PZT)	NO ₂	Room temperature	Pulsed laser deposition	99.4	80 ppm	N/a	N/a	9.6 Hz/ppm
[148]	SnO ₂ thin films	NO ₂	Room temperature	RF magnetron sputtering	433.9	20 ppm	2 s	45 s	1500 kHz/ppm
[153]	Polyaniline doped tungsten trioxide nanofiber	H ₂	Room temperature	Drop casting	107.2	N/a	40 s	1.67 s	7 kHz/ppm

sensor using photonic crystal fibers (PCFs) (Fig. 8c) which detected ammonia gas with a sensitivity of 63.18 % in order to monitor kidney failure [172]. In addition, NH₃ gas sensors can also be used as a medical biomarker for *Helicobacter pylori* (H. pylori) bacteria-induced stomach infections [157]. This was successfully demonstrated by Li et al. using a chemiresistive gas sensor based on CeO₂ coated copper (I) bromide (CuBr), as shown in Fig. 8d [8]. Based on the study, the sensor exhibited a 68 Rg/Ra response toward the exhaled breath of patients with H. pylori infections, which contained 50 ppb NH₃ [8]. NO gas sensors have been utilized as an asthma biomarker for symptoms like cough, and chest tightness [25, 173]. Typically, the breathing NO concentration for asthma patients exceeds 25 ppb [173]. Moon et al. fabricated porous thin films with chemiresistive properties based on WO₃ 1D nanostructures with 1D villi-like WO₃ nanofingers, using a room-temperature glancing angle deposition method for asthma detection [173]. Due to the large aspect ratio and porosity of the nanofingers, the sensor exhibited an excellent sensing response of 25 Rg/Ra at 200 ppb. Similarly, Hung et al. developed a SAW gas sensor based on PSSA doped PPy/WO₃/rGO hybrid nanocomposites for NO

gas [154]. In his research, a 912 Hz/ppm sensitivity and 2 mins response time were recorded for the detection of 1-110 ppb of NO gas. Apart from these, several researchers have developed and diagnosed diseases such as diabetes, monitoring of body fat, and employed VOC gases as lung cancer biomarkers. Acetone is one type of VOC gas, and one of the biomarkers for type-I diabetes. The exhaled acetone levels of diabetic patients may exceed 1800 ppb, while that of a healthy person is usually in the range of 300 to 900 ppb [25]. To detect diabetes, Righettonyet et al. used Si-doped WO₃ gas sensors, as shown in Fig. 9a [174]. In his work, a high sensitivity of 1.54 Ra/Rg at 500 ppb, a short response of 10 s, and a recovery time of 35 s were recorded. Similarly, Jeong et al. developed a diabetes diagnosis gas sensor based on Pt-decorated SnO₂ fibers, which showed an excellent response (141.92 Ra/Rg at 5 ppm), fast response time (15 s), and a lower detection limit of 5 ppb under 90 % RH at 350 °C [175]. Wang et al. reported the design of a wearable chemiresistor acetone gas sensor based on a 3D chitosan/graphene oxide bio-composite [176]. Due to the unique structure of the sensitive material, the sensor recorded 3.5 % to 96.7 % across the range of acetone concentrations from 0.05 to 100 ppm.

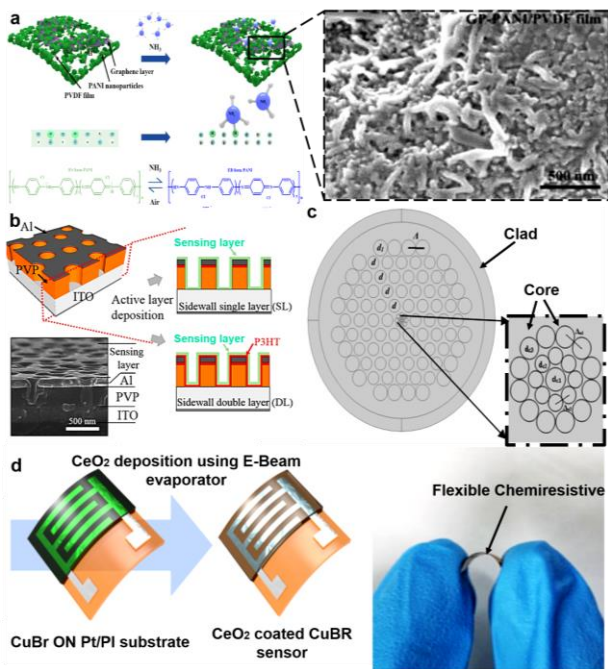


Fig. 8. (a) A flexible chemiresistive gas sensor based on graphene-PANI/PVDI. Reprinted from [23], Copyright (2021), with permission Elsevier. (b) Schematic design of a TFB material that used in kidney failure diagnosis. Reprinted from [24], Copyright (2019), with permission American Chemical Society. (c) Design of a hollow core fiber optic. Reprinted from [172], Copyright (2021), with permission Elsevier. (d) Flexible chemiresistive gas sensor based on CeO₂ coated CuBR. Reprinted from [8], Copyright (2018), with American Chemical Society.

Das et al. developed a cobalt chromite (CoCr₂O₄) film-based sensor, as shown in Fig. 9b, that showed a fast response (1.65 s) and recovery (62 s) [177]. Recently, Sen et al. developed a Pt and Sb₂O₃ soak for Fe₂O₃ thin films for diabetic patients [178]. In his development a 1.4 Rg/Ra sensitivity was obtained for the detection of 0.25 ppm acetone gas. On the contrary, VOC gas sensors can also be utilized as lung cancer biomarkers. Rahman et al. reported a QCM gas sensor based on pegylated lipopolymer, as shown in Fig. 9c [179]. In this study, four biomarkers, i.e., propanol, hexanal, ethyl benzene, and decane, were selected for detecting lung cancer. In this study, a sensitivity of 76 Hz for propanol, 172 Hz for hexanal, 267 Hz for ethyl benzene, and 254 Hz decane was reported. In another work, Kus et al. used a SAW sensor with a calix et al. to sensitive material to detect toluene as part of an early stage study of biomarkers for cancer diagnosis, as shown in Fig. 9d [180]. In this study, a higher sensitivity (1.6 μ Hz/ppm) was recorded in low 1 ppm of toluene. Similarly, Gregis et al. developed a lung cancer gas sensor biomarker using SiO₂ as a sensitive material [181]. In his study, it was able to detect toluene, o-xylene, and propanol, at very low concentrations (24 $\pm$ 3, 5 $\pm$ 1 and 21 $\pm$ 3 ppb respectively) [181]. In addition, the VOC gas sensor can also be used for fat burn monitoring. This is because acetone is a volatile byproduct of lipolysis, where a strong correlation reportedly exists between the breath acetone concentration, and the rate of fat loss. A work by Kudo et al. used a hollowfiber optic for body fat monitoring, as shown in Fig. 9e [182]. In this work, the authors

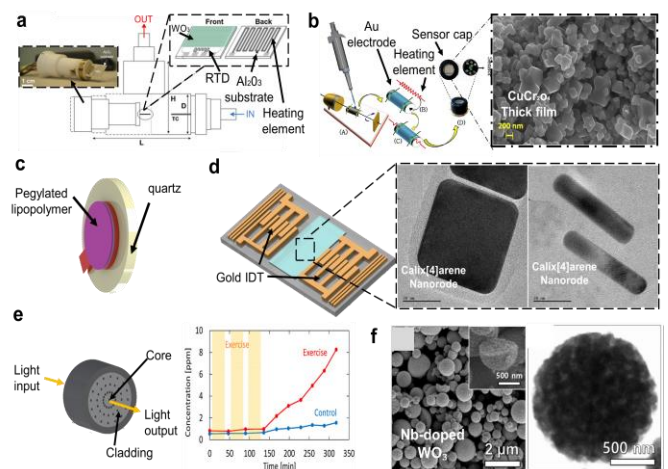


Fig. 9 (a) Chemiresistive gas sensor based on WO₃ sensing layer to diagnosis diabetic. Reprinted from [174], Copyright (2012), with permission Elsevier. (b) Schematic structure of a chemiresistive gas sensor based on cobalt chromite (CoCr₂O₄) film-based sensor. Reprinted from [177], Copyright (2021), with permission Elsevier. (c) QCM gas sensor based on pegylated lipopolymer. (d) Schematic structure of a SAW sensor based on calix [4] nanorode with SEM image Calix [4] nanorode. Reprinted from [180], Copyright (2021), with permission Elsevier. (e) Schematic Structure of a hollow core fiber optic sensor for fat burn monitoring. Reprinted from [182], Copyright (2021), with permission MDPI. (f) SEM image (left) and TEM image of Nb-doped WO₃ (right). Reprinted from [184], Copyright (2021), with permission Elsevier.

successfully demonstrated measuring acetone levels which increased after a workout [182]. Park et al. developed a portable MEMS gas sensor that contained two types of MOS gas sensors, i.e., *p*-type and *n*-type, that were designed to measure the body fat accurately [183]. The responses of the *p*-type gas sensor in this study decreased over time, from 0.85 Rg/Ra to 0.55 Rg/Ra, while the responses of the *n*-type sensor increased from 1.7 Rg/Ra to 6.7 Rg/Ra. Choi et al. developed a chemiresistive gas sensor based on niobium (Nb) doped WO₃ as shown in Fig. 9f [184]. In this study, the Nb-WO₃ sensor was also found to exhibit a fast response time (4 s) and a significantly lower detection limit (8.9 ppb).

IV. CONCLUSION

It is well recognized that MEMS gas sensors play an important role in many applications due to their ability to undergo miniaturization, as well as their sensing features. It is necessary to understand and compare these mechanisms since the basic of the MEMS gas sensors is based on detection methods. This article reviewed the major types of MEMS gas sensors based on electrochemical, optical and acoustic features, which have emerged over the past decades. A comprehensive discussion was presented, underlining the significance of these structures, working principles, sensing mechanisms, materials, and intended applications. In Table VII, a comparison of these major MEMS gas sensors is shown. Electrochemical gas sensors work based on the changes in the resistance of sensitive materials. Different types of electrochemical gas sensors, such as MOS and chemiresistive gas sensors are utilized for diabetic and stomach infection diagnosis, as well as monitoring of the

Table VII
SUMMARY AND PERFORMANCE COMPARISON OF THE MEMS GAS SENSORS

Major MEMS Gas Sensors	Working Principle	Advantages	Limitations	Applications
Electrochemical	Based on changes of resistance	Low cost [30, 33], short response time and recovery time [30], wide range of target gases [4, 118], and high sensitivity at high temperature [4].	The sensitivity of the sensitive material is reduced time by time because heat, low sensitivity and selectivity [118, 158], sensitive to environmental factors [32], and high power consumption [118, 4, 158].	Biomedical: Diabetic diagnosis [174, 177], stomach infection diagnosis [8], and Kidney disease diagnosis [24,34]. Gas: CO [42-44, 55, 71], H ₂ [29, 38, 41, 70], NO ₂ [30, 33, 39, 50, 72, 73], C ₅ H ₆ OH [32, 35, 36, 38], NH ₃ [14, 40, 62, 65], C ₃ H ₆ O [63], CH ₃ O ₃ [46], CH ₂ O [49, 69], and C ₅ H ₈ [31].
Optical gas sensor	Based on changes of light intensity	Long lifetime [3, 118], high selectivity and stability [118], higher sensitivity [109-111], insensitive to environmental change [4], operate in a wide range [4] and not easily affected by electromagnetic interference.	High cost [118], difficulty in miniaturization the design because of limitations due to the size of an external light source and photodetector [4,118], and easily affected by ambient light interference [118].	Biomedical: Fat burn monitoring [182] and kidney disease diagnosis [172]. Gas: H ₂ [85, 109-111], NH ₃ [103, 104, 107], CH ₃ OH [107, 112,114-116], CO ₂ [89, 106], NO ₂ [108], C ₃ H ₆ O [112], CH ₄ [82], H ₂ S [81, 83], C ₆ H ₁₄ [87], THF vapor [86], acetylene [85], and C ₂ H ₅ OH [101, 112].
Acoustic gas sensor	Based changes of frequency	High sensitivity [159], short response [4], fast response, long lifetime [4], low power consumption [4, 23], could be placed in harsh and rotating parts [4], small design [134, 138], and long-term stability.	Easily effected by temperature and humidity [118, 4] and difficult in handling during the fabrication process [4].	Biomedical: Lung cancer biomarker [179, 180]. Gas: HC [157], CO ₂ [159, 63], CO [134, 141-143], NO ₂ [145, 148, 169-171], NH ₃ [132, 133, 138-140, 149, 164-168], and H ₂ [158, 160-163].

industrial gases. The changes in the light reflection of the optical MEMS gas sensor have been applied for biomedical diagnosis and monitoring devices, such as diabetic diagnostics, and fat burn monitoring, respectively. Lastly, with much higher sensitivity and stability for acoustic MEMS gas sensors have been developed as lung cancer biomarker devices, and for industry monitoring of toxic gases such CO₂, CO, and NH₃.

Despite this progress, MEMS gas sensor research is still in its infancy, with numerous challenges ahead. For example, a MEMS MOS gas sensor has an excellent sensitivity toward toxic gases and VOCs. The sensitivity of the gas sensor, on the other hand, decreases over time, as it is heated for an extended period of time. By contrast, chemiresistive gas sensors have overcome this limitation, nonetheless, the sensitivity of the sensor is easily affected by its surrounding temperature. Likewise, optical gas sensors provide higher stability toward several gases and can operate across a wide range. However, the performance of an optical gas sensor is limited due to the size of the external light source, and the detector, which is difficult to minimize. On the other hand, acoustic gas sensors have the ability to be used as wireless gas sensors, which saves time and can be utilized in real-time monitoring. However, the sensitivity of the sensor is easily affected by humidity. According to reviewed literature, the majority of research is focused on individual MEMS gas sensors. Further optimization of sensitive materials and device configurations are required for biomedical applications, to ensure high sensitivity. With the progress of material science, bringing about new materials and nanomaterials, MEMS gas sensors have been improved in terms of sensitivity. In addition, with the development of doping methods on the materials have produced an effective way to improve the capabilities of the MEMS gas sensor. In conclusion, it is believed that with the higher sensitivity rates of the MEMS gas sensors, in the future, it will not only be used for current biomedical applications, but across a much wider range of such

applications.

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